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Numerical simulations of regolith sampling processes

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ABSTRACT

We present recent improvements in the simulation of regolith sampling processes in microgravity using the numerical particle method smooth particle hydrodynamics (SPH). We use an elastic-plastic soil constitutive model for large deformation and failure flows for dynamical behaviour of regolith. In the context of projected small body (asteroid or small moons) sample return missions, we investigate the efficiency and feasibility of a particular material sampling method: Brushes sweep material from the asteroid's surface into a collecting tray. We analyze the influence of different material parameters of regolith such as cohesion and angle of internal friction on the sampling rate. Furthermore, we study the sampling process in two environments by varying the surface gravity (Earth's and Phobos') and we apply different rotation rates for the brushes. We find good agreement of our sampling simulations on Earth with experiments and provide estimations for the influence of the material properties on the collecting rate.

1. Introduction

Regolith is a layer of loose, heterogeneous material. It includes dust, soil, brittle broken rock and can be found on terrestrial planets, moons and asteroids. ESA conducted a feasibility study for a European Phobos sample return mission, which was called Phootprint (Koschny et al., 2014; Barraclough et al., 2014), followed by a Phase A study called Phobos Sample Return (PhSR), which investigated a joint ESA/Roscosmos mission as well as an ESA standalone scenario. Phobos was chosen as a scientifically interesting destination due to its unknown formation process and as a unique opportunity to test some of the key components of a potential follow-up Mars sample return mission. Phobos has a semi-major axis of 9378 km and a sidereal orbital period of 0.3 days in bound rotation. Phobos is irregularly shaped and has dimensions of $27 \times 22 \times 18$ km. Phobos' internal structure is poorly constrained, Andert et al. (2010) provide values for the mean density of about 1876(20) kg/m^3 and a porosity of 30 ± 5%. The surface of Phobos is covered with regolith and the thickness of the layer varies between 5 m and 100 m (Basilevsky et al., 2014). Various spacecraft missions have investigated the moons of Mars, see the publication by Duxbury et al. (2014) for a complete review of Russian and American missions. However, no spacecraft has landed on Phobos yet.

The PhSR study is a technical baseline for a sample return mission to identify the key technological requirements and address their development requirements for a sample return mission. One of the major milestones is the design of a innovative sampling tool installed on the lander that will allow to collect at least 100 g of Phobos' surface material using a novel rotary brush mechanism. In addition to Phobos' material, a collected sample will presumably contain pieces of material originated from Mars.

Computer simulations and computer aided testing become more and more important in the field of spacecraft design. By the help of modern computers, we can investigate processes under physical conditions that are not easily available for experiments on Earth, e.g. low-gravity fields. Recently, new models for the dynamic behaviour of regolith have been developed using different numerical schemes: Schwartz et al. (2014) use a soft-sphere discrete element method (SSDEM) in the N-body gravity tree code `pkdgrav` to investigate low-speed impact simulations into regolith in support of asteroid sampling mechanisms in the context of the JAXA's Hayabusa and Hayabusa2 missions, and Bui et al. (2008) developed a model for granular flow using SPH in the context of solid mechanics combined with a Drucker-Prager yield criterion for plastic flow.

The study at hand is performed as part of ESA's PhSR mission and investigates the efficiency of the rotary brush sampling mechanism by numerical modelling with the latter SPH approach. As part of ESA's

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Mars Robotic Exploration technology development programme, a prototype of the rotary brush sampling tool was also tested under laboratory conditions on Earth and will be tested in microgravity on a parabolic flight (Ortega Juaristi et al., 2015). We developed a two-dimensional SPH model for one of the discussed sampling tool designs and performed several simulations with varying material properties of the simulated regolith. The main goal was to show the feasibility of the numerical method for the application of the sampling mechanism and to provide relative values for the sampling rate depending on the environmental properties. At first, we will present the physical model for regolith in the next section, followed by the numerical model and the implementation. In Section 4, we will show and discuss the simulations of the sampling process. We will give a conclusion in Section 5.

2. Physical model for regolith

The dynamical behaviour of regolith is usually described by a special constitutive model for soil. For the simulations carried out in this study, we applied the elastic-plastic model introduced by Bui et al. (2008). We will provide a short version of their derivation of the model in the following to point out the differences to our standard model for solid bodies. For the comprehensive treatise, we refer to their complete analysis in Bui et al. (2008). For an elastic-plastic material, the total strain rate tensor $\dot{\varepsilon}^{\alpha\beta}$, given by the derivation of the velocity $\mathbf{v}$ with respect to the coordinate system for small deformations

$$\dot{\varepsilon}^{\alpha\beta} = \frac{1}{2}\left(\frac{\partial v^\alpha}{\partial x^\beta} + \frac{\partial v^\beta}{\partial x^\alpha}\right), \tag{1}$$

can be written as the composition of a purely elastic and a totally plastic strain rate tensor

$$\dot{\varepsilon}^{\alpha\beta} = \dot{\varepsilon}_{\mathrm{e}}^{\alpha\beta} + \dot{\varepsilon}_{\mathrm{p}}^{\alpha\beta}. \tag{2}$$

The elastic strain rate tensor $\dot{\varepsilon}_{\mathrm{e}}^{\alpha\beta}$ is calculated by the three-dimensional version of Hooke's law

$$\dot{\varepsilon}_{\mathrm{e}}^{\alpha\beta} = \frac{1}{2\mu}\dot{S}^{\alpha\beta} + \frac{1-2\nu}{3E}\dot{\sigma}^{\gamma\gamma}\delta^{\alpha\beta}. \tag{3}$$

Here, $\dot{S}^{\alpha\beta}$ denotes the deviatoric stress rate tensor, $\dot{\sigma}^{\alpha\beta}$ is the stress rate tensor, μ, E, and ν are the material dependent parameters shear modulus, Young's modulus and Poison's ratio, respectively, and the Einstein sum convention is used ($\dot{\sigma}^{\gamma\gamma} = \mathrm{tr}(\dot{\sigma})$).

The plastic strain rate tensor is given by the following relation of the rate of change of the plastic multiplier λ and the plastic potential function g.

$$\dot{\varepsilon}_{\mathrm{p}}^{\alpha\beta} = \dot{\lambda}\frac{\partial g}{\partial \sigma^{\alpha\beta}}. \tag{4}$$

If the plastic potential g is equal to the yield function f of the material, the flow rule is called associated, and otherwise it is called non-associated. The plastic multiplier λ has to satisfy the conditions of the yield criterion: $\lambda = 0$ for $f < 0$ or $f = 0$ and $\mathrm{d}f < 0$, which corresponds to elastic or plastic unloading and $\lambda > 0$ for $f = 0$ and $\mathrm{d}f = 0$, which corresponds to plastic loading. Following (Bui et al., 2008), the two expressions for the elastic and the plastic strain rate tensors can be substituted into the equation for the strain rate tensor

$$\dot{\varepsilon}^{\alpha\beta} = \frac{1}{2\mu}\dot{S}^{\alpha\beta} + \frac{1-2\nu}{3E}\dot{\sigma}^{\gamma\gamma} + \dot{\lambda}\frac{\partial g}{\partial \sigma^{\alpha\beta}}, \tag{5}$$

which finally yields an expression for the general stress-strain relationship for an elastic-plastic material

$$\dot{\sigma}^{\alpha\beta} = 2\mu\left(\dot{\varepsilon}^{\alpha\beta} - \frac{1}{3}\dot{\varepsilon}^{\gamma\gamma}\delta^{\alpha\beta}\right) + K\dot{\varepsilon}^{\gamma\gamma}\delta^{\alpha\beta} - \dot{\lambda}\left(\left(K - \frac{2\mu}{3}\right)\frac{\partial g}{\partial \sigma^{\varphi\vartheta}}\delta^{\varphi\vartheta}\delta^{\alpha\beta} + 2\mu\frac{\partial g}{\partial \sigma^{\alpha\beta}}\right). \tag{6}$$

Here, K denotes the bulk modulus, which is given by the following expression

$$K = \frac{E}{3-6\nu}. \tag{7}$$

In order to calculate the stress in the regolith, one needs an expression for the rate of change of the plastic multiplier $\dot{\lambda}$. The general formulation for $\dot{\lambda}$ is given by

$$\dot{\lambda} = \frac{2\mu\dot{\varepsilon}^{\alpha\beta}\frac{\partial f}{\partial \sigma^{\alpha\beta}} + \left(K - \frac{2\mu}{3}\right)\dot{\varepsilon}^{\gamma\gamma}\frac{\partial f}{\partial \sigma^{\alpha\beta}}\delta^{\alpha\beta}}{2\mu\frac{\partial f}{\partial \sigma^{\varphi\vartheta}}\frac{\partial g}{\partial \sigma^{\varphi\vartheta}} + \left(K - \frac{2\mu}{3}\right)\frac{\partial f}{\partial \sigma^{\varphi\vartheta}}\delta^{\varphi\vartheta}\frac{\partial g}{\partial \sigma^{\varphi\vartheta}}\delta^{\varphi\vartheta}}. \tag{8}$$

Hence, as soon as the yield function f and the plastic potential function g are known for a specific material, the rate of change of the plastic multiplier $\dot{\lambda}$ can be computed, and consequentially, the stress rate tensor by the use of Eq. (6). The stress rate tensor is then integrated and the acceleration due to the stress is determined by the equation for the conservation of momentum

$$\frac{\mathrm{d}v^\alpha}{\mathrm{d}t} = \frac{1}{\varrho}\frac{\partial \sigma^{\alpha\beta}}{\partial x^\beta}, \tag{9}$$

where ϱ is the density of the regolith. The term k_{ext} corresponds to a specific volume force, e.g., an additional external gravity term.

The evolution of the mass density of the material is governed by the continuity equation

$$\frac{\mathrm{d}\varrho}{\mathrm{d}t} = -\varrho\frac{\partial v^\alpha}{\partial x^\alpha}. \tag{10}$$

In summary, the set of partial differential Eqs. (6), (9), (10) is sufficient to describe the dynamical behaviour of a solid, plastic body. The specific plastic behaviour of the material is given by the yield function f and the plastic potential function g. The plastic behaviour of granular media can be described by the model introduced by Drucker and Prager (1952). In the Drucker-Prager model, the yield function is given by the following relation between the first and second invariants of the stress tensor

$$f(I_1, J_2) = \sqrt{J_2} + \alpha_\phi I_1 - k_c = 0. \tag{11}$$

The invariants are given by the expressions

$$I_1 = \mathrm{tr}(\sigma) = \sigma^{\gamma\gamma} \quad \text{and} \quad J_2 = \frac{1}{2}S^{\alpha\beta}S_{\alpha\beta}. \tag{12}$$

The two material constants α_ϕ and k_c are called Drucker-Prager's constant and are related to the Coulomb's material constants cohesion c and angle of internal friction ϕ. The dependence between the four material parameters is different in plane strain and plane stress conditions. Throughout this study, we focus on plane strain conditions, where the relation is given by (see Bui et al. (2008))

$$\alpha_\phi = \frac{\tan\phi}{\sqrt{9 + 12\tan^2\phi}} \quad \text{and} \quad k_c = \frac{3c}{\sqrt{9 + 12\tan^2\phi}}. \tag{13}$$

In addition to the yield function f, the plastic potential function has to be determined to specify the stress-strain relationship. In the simulations carried out in this project, we use the non-associated flow rule

$$g = \sqrt{J_2} + 3I_1 \sin\psi, \tag{14}$$

where ψ denotes the dilatancy angle. We can write the derivative of the plastic potential function with respect to the stress tensor as